

PIGEONS' WAIT-TIME RESPONSES TO TRANSITIONS
IN INTERFOOD-INTERVAL DURATION: ANOTHER
LOOK AT CYCLIC SCHEDULE PERFORMANCE

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Recent developments reveal that animals can rapidly learn about intervals of time. We studied the nature of this fast-acting process in two experiments. In Experiment 1 pigeons were exposed to a modified fixed-time schedule, in which the time between food rewards (interfood interval) changed at an unpredictable point in each session, either decreasing from 15 to 5 s (step-down) or increasing from 15 to 45 s (step-up). The birds were able to track under both conditions by producing postreinforcement wait times proportional to the preceding interfood-interval duration. However, the time course of responding differed: Tracking was apparently more gradual in the step-up condition. Experiment 2 studied the effect of having both kinds of transitions within the same session by exposing pigeons to a repeating (cyclic) sequence of the interfood-interval values used in Experiment 1. Pigeons detected changes in the input sequence of interfood intervals, but only for a few sessions—discrimination worsened with further training. The dynamic effects we observed do not support a linear waiting process of time discrimination, but instead point to a timing mechanism based on the frequency and recency of prior interfood intervals and not the preceding interfood interval alone.

Key words: temporal discrimination, cyclic schedule, transitions, linear waiting, interfood interval, key peck, pigeons

Most mammals and birds are able to detect and learn about temporal regularities in their environment. Perhaps the simplest example of this ability is performance during fixed-interval (FI) reinforcement schedules in which a response is reinforced if it occurs after a fixed amount of time has elapsed since the presentation of the preceding reinforcer. Reinforcers, usually food for a hungry animal, delivered in this way effectively divide a session into intervals of time marked by reinforcement (interfood interval; IFI). The typical steady-state pattern of responding within an IFI is a postreinforcement pause (or wait time) before the

first response and an acceleration in responding as time to the next reinforcement approaches (see Ferster & Skinner, 1957, for several examples). The organization of behavior within an IFI indicates that the animal has learned something about the duration of the IFI. Specifically, longer IFIs generally produce longer (but more variable) wait times (e.g., Gibbon, 1977; Richelle & Lejeune, 1980; Schneider, 1969). The ability to refrain from responding when reinforcement is unlikely (i.e., immediately following reinforcement) and to do so according to the prevailing IFI duration is called *temporal discrimination*.

A substantial amount of research has focused on the steady-state properties of temporal discrimination, where the behavior of interest is that obtained after many sessions (and often hundreds of trials) of exposure to a single condition. Many quantitative properties have been discovered (e.g., Gibbon, 1977), and several theories have been developed (e.g., Church & Broadbent, 1991; Gibbon, 1977; Killeen & Fetterman, 1988). However, relatively little attention has been given to studying the dynamics of temporal discrimination. This may have been difficult to do in the past, in part because temporal discrimination was assumed to be intrinsically slow;

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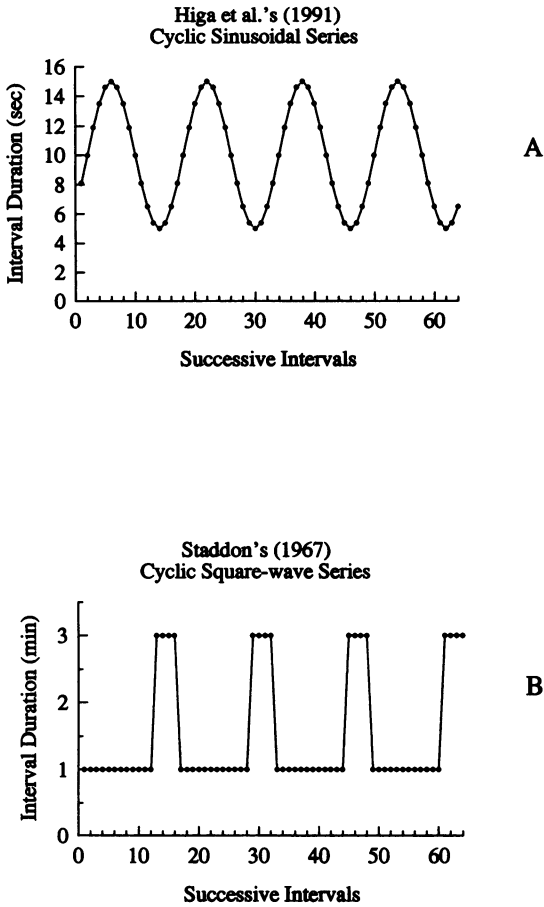


Fig. 1. A. Example of the cyclic sinusoidal sequence used by Higa et al. (1991). Each cycle consists of 16 IFI durations ranging from 5 to 15 s. B. Illustration of the cyclic square-wave sequence used by Staddon (1967). Each cycle consists of 12 FI 1-min IFIs followed by four FI 3-min IFIs.

indeed, steady-state performance under the usual conditions required many sessions to develop. Fortunately, there is recent evidence that temporal discrimination can, under certain conditions, develop rapidly, thereby permitting the study of dynamics, and thereby possibly leading to a better understanding of the underlying mechanism.

One example of rapid timing comes from a study by Higa, Wynne, and Staddon (1991). In one experiment they found that pigeons were able to track a cyclic (repeating) sinusoidal sequence of IFIs ranging either from 5 to 15 s or from 30 to 90 s (an example of the shorter range of IFIs is shown in Figure 1A).

A

B

Pigeons tracked the sequence in the sense that the output pattern of wait times looked like the input sequence of IFI durations. Specifically, the wait time in one IFI was proportional to the duration of the preceding IFI: Correlations between the input pattern of intervals and the output pattern of wait times were often highest at phase lags of one or zero. For example, the shortest or longest wait time was often found in the interval following the shortest or longest programmed interval (Phase Lag 1). Temporal discrimination developed after a few sessions of exposure (sometimes by the second or third session), even though the number of cycles and starting phase within a cycle varied from one session to the next. The speed at which this discrimination developed was surprising, because earlier experiments often reported that 30 sessions or more were required to achieve stable performance on single-interval schedules within the range of intervals that Higa et al. used in the same session (e.g., Schneider, 1969).

Higa et al. (1991) suggested that the simplest possible mechanism for their finding was that a pigeon adjusts its wait time in one interval, IFI_n , according to the duration of the immediately preceding interval, IFI_{n-1} . Wynne and Staddon (1988) referred to this as a one-back (linear waiting) process. It is a context-free or memory-free process in the sense that wait times will be proportional to the immediately preceding IFI duration and that other IFIs, two or more back, should not affect performance. Direct evidence for this kind of process was found by Higa et al. in a subsequent experiment, in which they measured pigeons' responses to a single short IFI (5 s in duration, called an *impulse*) that was interpolated in a series of longer IFIs (all 15 s in duration). They discovered that pigeons' wait times in the IFI immediately following an impulse IFI were shorter than usual, and wait times in subsequent IFIs quickly recovered to preimpulse levels. These effects were observed early in training, did not change systematically across sessions, and clearly supported a linear waiting process for temporal discrimination.

However, notice that linear waiting always predicts good temporal discrimination regardless of the order or combination of IFIs. That is, a pigeon's output pattern of wait times should mirror the input sequence of IFIs such

that the duration of one IFI is highly predictive of wait time in the next. Yet, the results from several experiments show that pigeons often fail to discriminate: Wait times are approximately the same duration within each IFI of a sequence of varying IFI durations. For example, it is well known that steady-state performance on variable-interval (VI) reinforcement schedules is characterized as a constant rate of responding throughout an IFI, and from one IFI to the next, with few postreinforcement wait times (see Ferster & Skinner, 1957, for many examples). Pigeons are also unsuccessful at discriminating relatively simpler and predictable IFI sequences. For instance, Staddon (1967) found that pigeons did not learn to track a cyclic square-wave sequence of 12 1-min IFIs followed by 4 3-min IFIs even after 30 or more sessions of exposure (Staddon's square-wave sequence is shown in Figure 1B; see Innis, 1981, and Innis & Staddon, 1970, for more examples).

Why can pigeons learn relatively complex reinforcement schedules like the sinusoidal sequence in Figure 1A, but are apparently unable to learn the square-wave sequence (shown in Figure 1B) that is comprised of only two IFI values? It is unlikely that cycling per se is a factor, because rapid tracking is observed on cyclic sinusoidal sequences. It is also unlikely that poor discrimination performance is directly related to the range of the IFIs: Although pigeons fail to track square-wave sequences of 1- and 3-min IFIs (Staddon, 1967), 1- and 2-min IFIs, or 1- and 6-min IFIs (Innis & Staddon, 1970), the pigeons in the Higa et al. (1991) study were able to discriminate a cyclic sinusoidal sequence of IFIs ranging from 0.5 to 1.5 min.

Instead, successes and failures to track may somehow depend on the nature of the transition in IFI duration in these schedules: It is smooth and progressive in multivalued sinusoidal sequences and is abrupt in two-valued square-wave ones. At present, we do not know exactly how an abrupt change in IFI duration disrupts temporal discrimination; information about this effect might lead to a better understanding of timing. The following experiments address this question and further explore the conditions that produce successful and unsuccessful temporal discrimination. In Experiment 1 we divided the cyclic square-wave se-

quence into its components and examined pigeons' responses to a single decrease (step-down) or increase (step-up) in IFI duration. Then, in Experiment 2 we studied how the occurrence of both kinds of transitions, within the same session, affects the discrimination process.

EXPERIMENT 1: EFFECTS OF A SINGLE TRANSITION TO SHORTER OR LONGER IFIs

In this experiment, we examined pigeons' responses to a single, nearly unpredictable, step-wise increase or decrease in IFI duration. Although there is some evidence that pigeons can successfully track a transition to longer interval durations, the data do not rule out the possibility that discrimination was based on cues other than the IFI sequence. In particular, Keller (1973) presented pigeons with a daily sequence of 19 20-s IFIs followed by 41 180-s IFIs, each interval programmed according to an FI schedule. After many sessions of exposure, he found that pigeons' wait times followed the abrupt (step-up) change in IFI duration: Wait times were longer (although more variable) during the 180-s IFIs than during the shorter ones. However, because his pigeons always received the same pattern of IFIs and had many sessions of training on this schedule, they may have based their responses on cues other than the input sequence (e.g., the time since the start of the session).

Our experiment differs from Keller's, in that we looked at the effects of IFIs changing in both directions (increasing and decreasing); we minimized cues that pigeons may base their responses on by varying the point of transition to longer or to shorter intervals within a session; we used IFIs that changed from prestep to poststep on the order of 1:3 (Keller used a 1:9 ratio); individual IFIs were programmed according to a modified FT schedule; and, finally, we studied the development of discrimination during the first few sessions of exposure.

Specifically, we asked: (a) Can pigeons' behavior track an unpredictable step-wise transition in IFI duration? If so, what are the dynamic properties? (b) Does the direction of change make a difference? (c) To what extent does varying the location of the transition in-

Response-Initiated Delay (RID) Interfood Interval

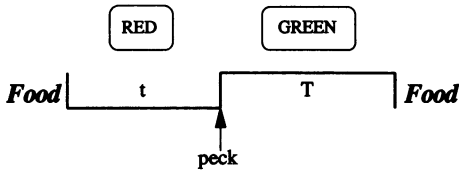


Fig. 2. Illustration of a single response-initiated-delay (RID) interfood interval. See text for further explanation.

terval within a session affect temporal discrimination?

METHOD

Subjects

Two adult White Carneau and 2 adult Silver King male pigeons served as subjects and were maintained at approximately 85% of their free-feeding body weights. Only B18 and B167 had experience with other temporal discrimination tasks; B299's and B931's only experience was with an autoshaping procedure. Weights sometimes increased above 85%; to limit this gain, pigeons were sometimes not studied every day.

Apparatus

The experiment was conducted in a standard operant conditioning chamber (43 cm wide, 38 cm deep, and 34 cm high). On the front panel was a single key (3 cm in diameter) that could be back-illuminated either red or green. Grain was presented through an aperture (4.5 cm by 5.7 cm), 12.8 cm below the response key, center to center. A fan masked extraneous noise, and a houselight in the center of the ceiling illuminated the chamber. The entire chamber was housed in a sound-attenuating box. Experimental events were controlled and recorded by a computer in an adjacent room.

Procedure

All subjects were exposed to three conditions: no-step, step-down, and step-up. Each condition was in effect for 10 sessions, with

the exception of the no-step condition for Subjects B299 and B931—they received 14 sessions. The order of conditions differed across subjects: B18 and B299 received the no-step, step-up, then step-down conditions; B167 and B931 received no-step, step-down, then step-up.

In all conditions, a session began with a reinforcer (2-s access to mixed grain) followed by 100 interfood intervals (IFIs), programmed according to a response-initiated-delay (RID) schedule (e.g., Shull, 1970; Wynne & Staddon, 1988). This schedule is equivalent to a signaled conjunctive fixed-ratio (FR) 1, fixed-time (FT) x schedule, where x was either 5, 15, or 45 s depending on the schedule and condition. As illustrated in Figure 2, each IFI began with a delivery of food. The response key was illuminated red, and the pigeon could wait any amount of time (t) before responding. The first key peck changed the light from red to green; subsequent key pecks were recorded but had no programmed effect. After an additional time T , the green light was extinguished, reinforcement was given, and the next IFI began. The total IFI duration was held at a predetermined programmed value: $t + T = \text{IFI duration}$. Notice that food delay, T , was determined by the IFI duration minus t . For example, if the programmed IFI duration was 15 s and the pigeon's wait time (t) was 5 s, then the delay to food (T) was set at 10 s; if $t = 9$ s, T was set at 6 s, and so forth. If the pigeon waited longer than the IFI duration, the animal received a flash of green for 0.5 s and food was delivered.

For the no-step condition, all 100 IFIs were programmed to be 15 s in duration. In the step-down and step-up conditions, the IFIs changed from 15 to 5 s or from 15 to 45 s, respectively. The transition to shorter or longer IFIs occurred at random times within a session, with two constraints: (a) At least 50 IFIs preceded a transition, and (b) each session always ended with a minimum of 15 shorter or longer IFIs. Thus, a transition could occur any time after IFI 50 but before IFI 86.

Fig. 3. Mean wait times during the 15 IFIs preceding (numbered -15 through -1 on the x axis) and following (numbered 1 through 15 on the x axis) a transition to shorter or longer IFI durations in Experiment 1. The solid vertical line (0 on the x axis) marks the transition. The results from the no-step condition are shown as unfilled circles, the step-down condition as filled circles, and the step-up condition as unfilled inverted triangles. Wait times have been averaged across all sessions.

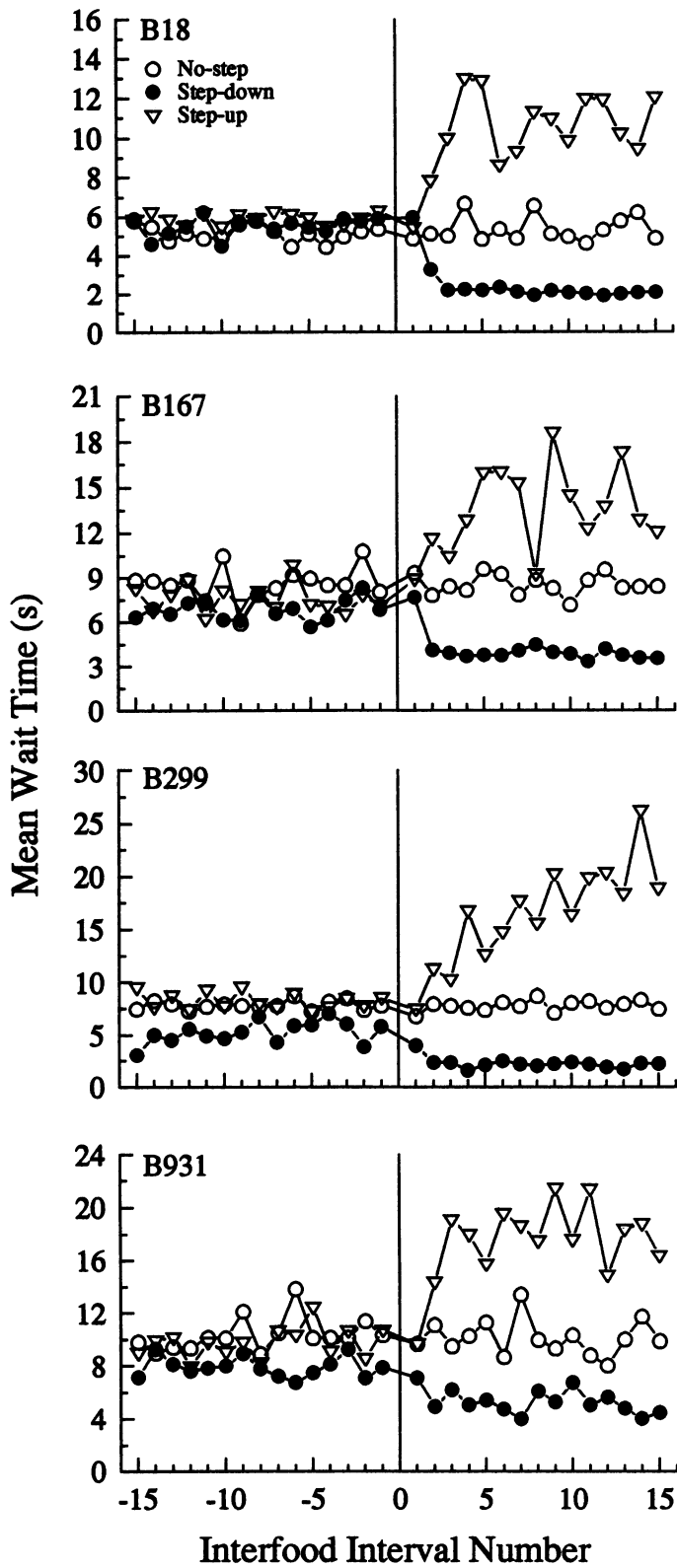


Table 1

Mean and standard deviation of the results shown in Figure 3, based on the 15 interfood intervals preceding (prestep) and following (poststep) a transition.

Subject	Condition	Prestep		Poststep	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
B18	No-step	5.17	0.43	5.37	0.64
	Step-down	5.53	0.48	2.45	1.02
	Step-up	5.92	0.29	10.31	2.04
B167	No-step	8.61	1.15	8.58	0.68
	Step-down	6.88	0.74	4.15	1.02
	Step-up	7.61	0.96	13.44	2.83
B299	No-step	7.89	0.42	7.81	0.50
	Step-down	5.27	1.05	2.29	0.54
	Step-up	8.29	0.78	16.45	4.71
B931	No-step	10.38	1.28	10.16	1.34
	Step-down	7.93	0.76	5.34	0.91
	Step-up	9.77	1.16	17.41	2.97

RESULTS

Did pigeons' behavior track the changes in IFI duration? Because the transition to shorter intervals in the step-down condition (and to longer intervals in the step-up condition) occurred at a different point within each session, a coherent method for analyzing wait times across sessions was needed: We extracted wait times during the 15 IFIs preceding and following a transition in each session, and then calculated a mean wait time across all sessions for these extracted intervals (for the no-step condition an arbitrary transition point was assumed for each session). Thus, for all conditions only 30 of the 100 IFIs were considered. The results of this averaging method are shown in Figure 3. The mean and standard deviation of the prestep and poststep IFIs are provided in Table 1.

During the no-step condition, the overall wait times for each subject ranged from approximately 5 to 10 s in duration, and none of the subjects showed significant changes in wait times before and after a "transition." Figure 3 and Table 1 confirm that B18's mean wait times changed little from 5.17 (prestep) to 5.37 s (poststep), B167 from 8.61 to 8.58 s, B299 from 7.89 to 7.81 s, and B931 from 10.38 to 10.16 s.

However, there are significant changes in wait times about transition points in the step-down and step-up conditions. In the step-down condition, all subjects showed a decrease in

wait times following a transition to shorter IFI durations. For example, Subject B18's average wait time from prestep to poststep decreased from 5.53 to 2.45 s. In a corresponding manner, all subjects increased their overall wait times during the transition to longer intervals in the step-up condition. For instance, Subject B167 increased its mean wait time from 7.61 to 13.44 s. The magnitude of change in poststep wait times was larger between no-step and step-up than between no-step and step-down, as would be expected if wait times were based on the prevailing IFI duration (compare mean poststep wait times, across conditions, in Table 1).

In addition to differences in the degree of change, the experimental conditions produced different patterns of wait times during the poststep phase of each condition. Scanning wait times in Figure 3 indicates that wait times reached a final value more quickly in the step-down condition (i.e., across earlier poststep IFIs) and were generally less variable. To illustrate, in the step-down condition, wait times during poststep IFI 1 (that is, the first 5-s IFI) for all subjects were at about the same level as prestep intervals. This effect is not too surprising: The occurrence of a transition was unpredictable; hence, wait times in this IFI should be approximately the same as that during prestep (15-s) IFIs. Next, there was a drop in wait times at poststep IFI 2, and wait times changed relatively little during subsequent poststep IFIs. This effect is clearest for Subjects B18, B167, and B299: Wait times during IFIs 2 through 15 were lower than prestep wait times and remained relatively constant. Subject B931's poststep wait times appeared to be more variable; however, they were still lower than those during prestep IFIs. In contrast to the rapid change seen in the step-down condition, wait times during the step-up condition adapted to the prevailing IFI duration more gradually; that is, although there was an immediate increase in wait time during poststep IFI 2, wait times continued to change across subsequent (later) poststep IFIs. For example, B299's wait times increased across most of the poststep IFIs, from IFI 1 through 15; the remaining subjects showed more limited increases in wait times through poststep IFIs 3 (B931), 4 (B18), and 5 (B167).

At what point in training do wait times begin to increase or decrease in response to a

transition in IFI duration? In other words, did the within-session poststep changes seen in Figure 3 appear on the first session of exposure or did they develop later in training, during the last few sessions? One way to address this question is to look at the earliest poststep IFI, in which we might observe a change in wait time and track those changes across sessions. Poststep IFI 1 will not be informative because it occurred at unpredictable times in each session. However, it can be used as a baseline measure of wait times prior to a transition. Poststep IFI 2 is probably a better candidate, because it is the first opportunity that a subject has to adjust its wait time in response to a transition to shorter or longer IFIs. Figure 4 presents wait times from these two poststep IFIs in cumulative plots: For each session the wait times during poststep IFIs 1 and 2 were extracted and then accumulated across sessions.

Cumulative plots like those in Figure 4 show whether wait times during poststep IFIs 1 and 2 (from Figure 3) differed in each session and at what point in training this difference occurred. Specifically, differences in slope (overall and from one data point to the next) gauge wait-time differences: Smaller slopes indicate accumulation of smaller wait times across sessions, and larger slopes specify the accumulation of longer wait times. If the two series are parallel to each other (i.e., they have the same slope), then there is no difference in wait times—the increment in wait time is the same for each series, from one session to the next. Although each series consists of only a few data points (10, because there was only one transition per session) and although only two of the 15 poststep IFIs are considered, there is a slight suggestion that decreases (step-down) and increases (step-up) in poststep wait times developed at different points in training.

First, in the step-down condition, the overall slope for IFI 2 is *lower* than that for IFI 1. In comparison, the slope for IFI 2 is generally *higher* in step-up. Second, there is some indication that wait times in IFI 2 began to decrease (step-down) or increase (step-up) at different points in training. Specifically, cumulative wait times began to diverge earlier in step-down. To illustrate, B18's wait time was shorter in IFI 2 than in IFI 1 during Session 1 (compare filled and unfilled circles for Session 1 in Figure 4). Wait times during

IFI 1 continued to grow across sessions by approximately the same amount, and to a lesser extent during Sessions 9 and 10. In contrast, wait times in IFI 2 increased across sessions at a much lower rate—there were occasional abrupt increases in wait times (e.g., Sessions 5 and 7), but overall slopes began to differ early in training. The results for B167 also suggest that wait times in IFI 2 were shorter than in IFI 1 early in training (by Session 2) and remained generally lower throughout. The results for B299 and B931 are less clear, and suggest that their wait times did not change as rapidly across sessions. For example, B299's wait times began to differ by Session 2, but there were occasional sessions (e.g., Sessions 3 and 4) in which wait times during IFIs 1 and 2 grew by the same amount, suggesting few, if any, differences in wait times, and hence, indicating little difference in wait times for that session.

The results from the step-up condition, in contrast to step-down, suggest that increases in poststep IFI 2 did not occur until later in training. For example, B18's cumulative wait times did not begin to diverge until Session 6, as compared to Session 2 during step-down. Again, as in the step-down condition, some birds showed occasional abrupt changes in wait times, and in some sessions wait times in poststep IFIs 1 and 2 appeared to increment by the same amount. Nonetheless, Figure 4 hints, for some subjects and in a general sense, that the wait time in IFI 2 began to differ from IFI 1 at different points in training—earlier for step-down and later for step-up.

Finally, two additional effects, seen in Figure 3 and Table 1, are worth noting. First, there was a small global effect of the step-down condition; that is, wait time in the prestep IFIs preceding a transition was somewhat reduced in the step-down condition compared to the no-step condition. This is clearest for Subjects B299 and B931, whose mean prestep wait times changed from 7.89 to 5.27 s (B299) and from 10.38 to 7.93 s (B931). Subject B167 also had a small effect of this sort. Only Subject B18 showed little change in prestep wait times across conditions. Second, poststep wait times were noticeably more variable in the step-up condition than in the step-down condition. The standard deviations of poststep IFIs (Table 1) are larger during the step-up condition; for instance, B18's standard deviation increased

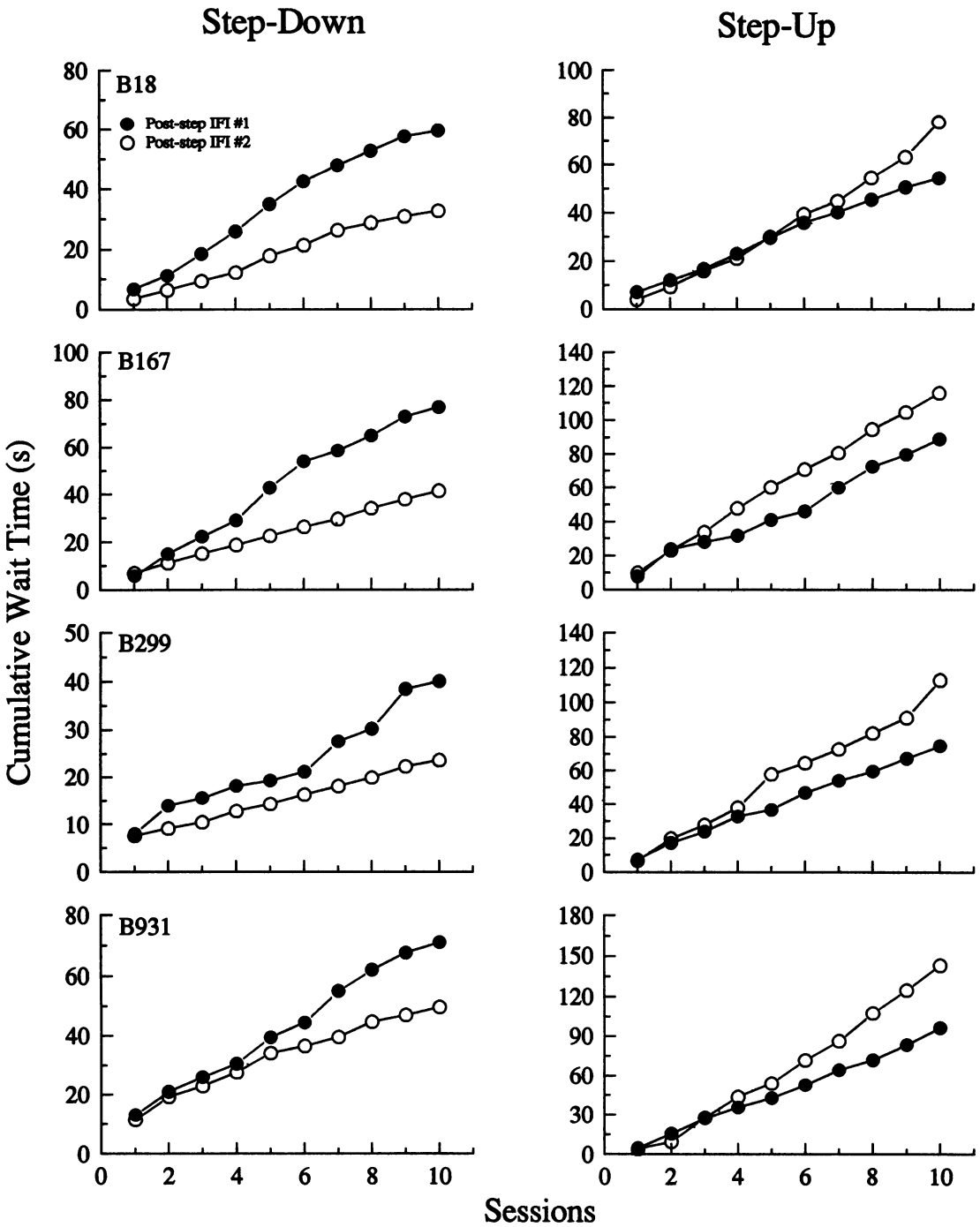


Fig. 4. Cumulative wait times for poststep IFI 1 (filled) and 2 (unfilled) from the step-down (left column) and step-up (right column) conditions of Experiment 1. Note that the slope of each series indicates how wait times changed across sessions—steeper slopes suggest longer wait times.

from 1.02 in the step-down condition to 2.04 in the step-up condition, B167's increased from 1.02 to 2.83, B299's increased from 0.54 to 4.71, and B931's increased from 0.91 to 2.97.

DISCUSSION

The results from this experiment add to and extend Keller's (1973) study by clearly showing that pigeons are able to track an unpredictable step-wise transition in IFI duration. In addition, we discovered that the direction of change produced different effects across poststep IFIs within a session and between sessions. The step-down condition revealed that wait times decreased immediately in response to a decrease in IFI duration: Lower wait times were seen as early as poststep IFI 2 and remained at about the same level across subsequent poststep IFIs. Furthermore, the decrease in wait times was evident early in training, during the first few sessions of exposure. In contrast, although an immediate increase in wait times was also observed during the step-up condition, wait times continued to increase across more poststep IFIs, and often began to occur after more sessions had elapsed.

The gradual adaptation of wait times to longer IFI durations, across sessions, has also been observed by Wynne and Staddon (1992). In one experiment, they gave pigeons blocked sessions of exposure to IFIs programmed according to a variation of the RID schedule that we used. In each block, the delay to food (Parameter T , see Figure 2) was set to either 20, 40, or 80 s. They reported that pigeons' wait times adjusted more rapidly to a particular IFI duration when it was preceded by blocked sessions of a longer IFI duration (long to short) than when it was preceded by blocked sessions of shorter IFIs (short to long).

Together, their results and the results from our experiment indicate that short IFIs (less than 20 or 30 s) are much more effective in controlling behavior than are longer ones. Is there an explanation for this effect? Higa et al. (1991) and Wynne and Staddon (1992) have argued that short wait times have an advantage over longer wait times in the following sense. Suppose an animal is given several 15-s IFIs like those preceding a transition in our experiment. Its tendency to respond will be a fraction of that IFI, say 5 s. If the next IFI is 45 s, the animal will probably base its wait

time on the preceding IFI duration and wait for 5 s. But what will the animal do if presented with still another 45-s IFI? It will probably respond "short" at 5 s. Why? Although it has a tendency to respond "long" (based on the preceding 45-s IFI), it still has a strong, though weakening, tendency to respond short (based on all the other 15-s IFIs it has recently experienced). Thus, the animal responds short not necessarily because it fails to learn about the 45-s IFI, but because its weakened tendency to respond short preempts responding at longer wait times. Eventually, the tendency to respond short will dissipate altogether, and we may eventually see longer wait times. In other words, under some conditions, discrimination may be affected by a kind of proactive interference, stemming from recent experience with short IFIs. Notice that the argument for going in the opposite direction, from long to short IFIs, predicts an immediate decrease in wait times: A small tendency to respond short (even after just one short IFI) preempts longer wait times.

Staddon and Higa (1991) have proposed a real-time model for temporal learning with these dynamic properties. It is a model in which an animal's memory for past events is a dynamic process that changes with time. The model—called a *diffusion-generalization model*—assumes that the tendency to respond at each postfood time is linked to the duration of previous IFIs according to the frequency and recency (age) of those IFIs: Reinforcement at a particular postfood time strengthens the tendency to respond at that time, and this tendency generalizes to other postfood times in memory (i.e., that have been experienced); furthermore, the tendency to respond decays with time according to a diffusion process. Response strength is based on the overall levels of excitation across the continuum (representation) of postfood times.

A full description of the model is beyond the scope of this paper. In short, it predicts that short IFIs are more effective in controlling behavior, and that the degree to which they influence responding depends on how long ago they occurred—yesterday or just a few IFIs ago; the model also predicts that many IFIs (short or long) will have more persistent effects than just one. The model seems to predict the kinds of effects we observed in this experiment.

More important, it suggests that the failure to track cyclic square-wave sequences may be tied to the different dynamic effects on behavior that downward and upward transitions in IFI duration produce. We studied the nature of these effects in the next experiment.

EXPERIMENT 2: EFFECTS OF CYCLIC TRANSITIONS IN IFI DURATIONS

Experiment 1 demonstrated that pigeons are able to adjust appropriately their wait times to a single abrupt change in IFI duration. Therefore, failures to discriminate during cyclic square-wave schedules are probably not the result of a transition *per se* in IFI duration. Instead, the different dynamic properties associated with transitions in IFI duration may explain failures to track. It would be instructive to look at the results from prior studies on various cyclic schedules (e.g., Innis & Staddon, 1970; Staddon, 1967); unfortunately, these studies did not address how or whether temporal discrimination developed during the initial sessions of exposure, and only data from steady-state performance were presented. Thus, our aim in the next experiment was to study how cyclic transitions in IFI duration, within the same session, affect discrimination. In order to have some basis for comparison with Experiment 1, we exposed pigeons to a cyclic sequence of the same IFI durations used in that experiment.

METHOD

Subjects and Apparatus

The subjects and apparatus were the same as those used in Experiment 1.

Procedure

The experiment began with 10 sessions of a baseline condition. Each session consisted of 100 15-s IFIs programmed according to the RID schedule used in Experiment 1. Next, each subject was given 10 sessions of training on a three-valued sequence of intervals that was repeated throughout the session in the following way: 15, 5, 15, 45, 15, 5, 15, 45, and

so forth. The starting point within a cycle was randomized across sessions. Thus, on any particular day a subject saw one of the following series: 15, 5, 15, 45, . . . ; 5, 15, 45, 15, . . . ; 15, 45, 15, 5, . . . ; 45, 15, 5, 15, . . . Sessions ended after 100 of these intervals had elapsed.

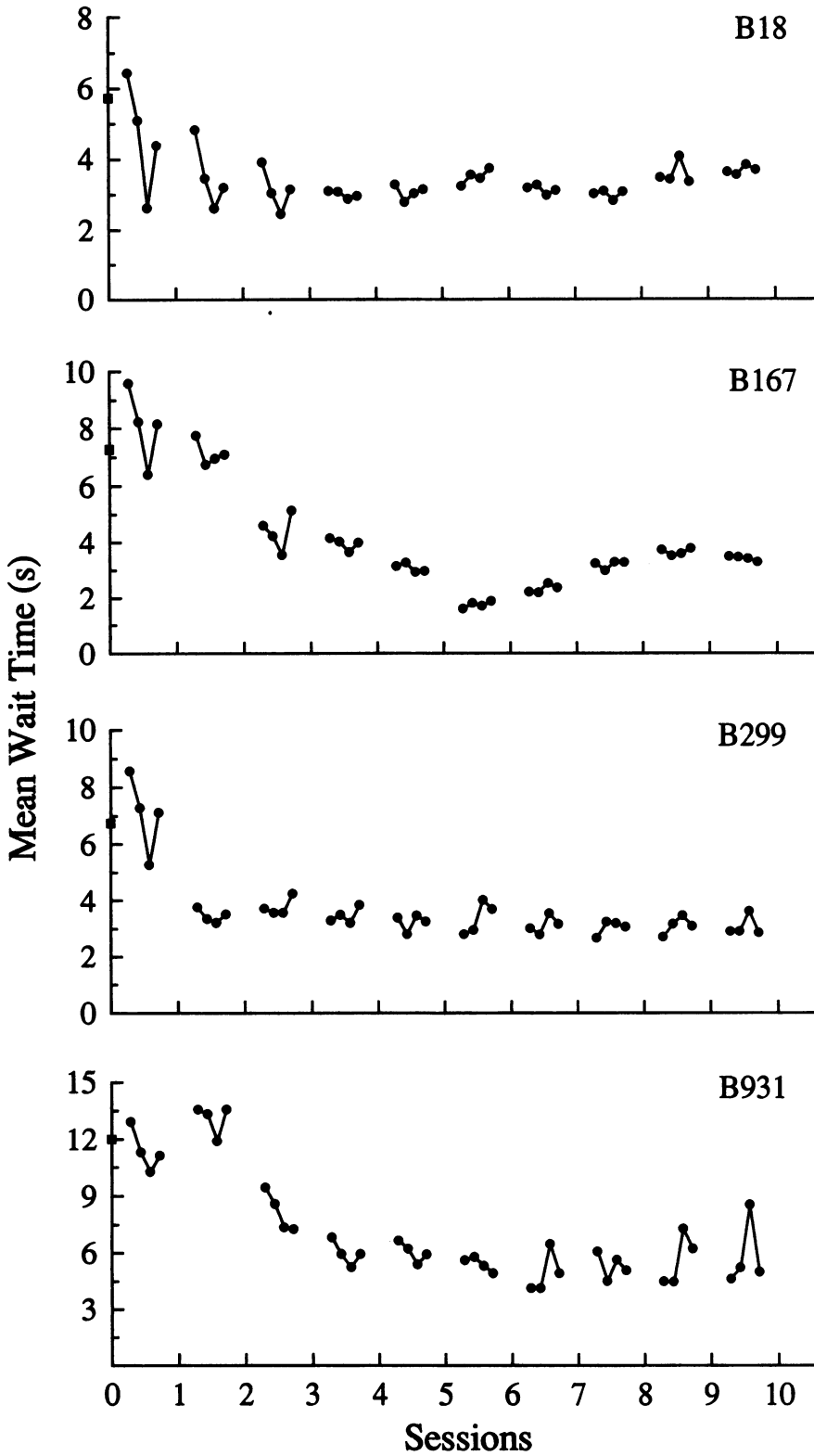
RESULTS AND DISCUSSION

Figure 5 presents the mean wait time during each interval of a single cycle. The results from each session are shown in groups of four. Individual data points within a group mark the mean wait time during the 15, 5, 15, and 45-s IFI of a cycle; the wait times for each session are shown in terms of the same starting point within a cycle for easier comparison across sessions. Means include wait times from all IFIs except those from the first four (first cycle) from each session. Also, mean wait time from the baseline condition is shown as a filled square on the *y* axis and is based on all sessions and IFIs.

Did the pigeons learn to track the cyclic sequence of IFIs? How was overall performance affected? First, overall wait times (Figure 5) tended to decrease across sessions, becoming shorter than those observed during baseline and the first session of exposure. The wait times for Subjects B167 and B931 became gradually shorter across sessions, whereas wait times for Subjects B18 and B299 decreased more rapidly and changed relatively little across sessions.

Second, notice that during Session 1, the wait times for all pigeons formed a distinctive asymmetrical V pattern, comprised of a long wait time during the first IFI and followed by a shorter wait time during the second IFI, another decrease in wait time in the third IFI, and then a moderate increase during the fourth IFI. The significance of this V pattern is that wait times were not proportional to the IFI duration in which it occurred (IFI_n). If wait times are proportional to the IFIs of the cycle in which it was measured (15, 5, 15, 45), then the wait times would form an asymmetrical V with the right limb longer (higher) than the left. Instead, wait times appeared to depend on the duration of the immediately preceding

Fig. 5. Mean wait times during a cycle of interfood intervals, calculated for each session in Experiment 2 (see text for averaging method). Wait times appear as groups of four filled circles connected by a line. The first set of four data points is from Session 1, the second set is from Session 2, the third set is from Session 3, and so forth.



interval (IFI_{n-1}): Wait times were shortest following a 5-s IFI, longest after a 45-s IFI, and intermediate following a 15-s IFI. Moreover, notice that this pattern is evident during the very first session of exposure but disappears across sessions. For example, Subject B18's wait times tracked the input cycle (according to the previous IFI duration) in Sessions 1, 2, and 3, but by Session 4 its wait times were undifferentiated and converged to a single value, about 3.4 s. The remaining subjects also appeared to track the input cycle, but only in Session 1. There is some evidence of tracking in later sessions (e.g., B167, Session 3, and B931, Session 4), but the effects are not as strong.

In sum, pigeons are able to track a cyclic sequence of IFIs with many transitions and variable starting points, but for only a few sessions. During the first training session, pigeons tracked by producing a wait time in one IFI that was proportional to the previous IFI duration. However, with further training wait times were no longer proportional to the preceding IFI; they were shorter relative to baseline levels and were approximately the same across all IFI durations. These results only partially support a one-back linear-waiting mechanism for time discrimination (e.g., Staddon, Wynne, & Higa, 1991; Wynne & Staddon, 1988). Deterioration in performance is likely to depend on factors other than the preceding IFI duration.

GENERAL DISCUSSION

When exposed to a sequence of identical IFI durations, as in fixed-interval schedules, pigeons produce wait times that are proportional to the duration of the IFI (scalar timing; Gibbon, 1977). When two different IFI durations are combined in the same session, discrimination depends on the arrangement of intervals and training history. For example, pigeons have not discriminated a simple and predictable sequence of IFIs that repeats throughout a session, either through strict alternations of these values (e.g., Innis, 1981) or when the intervals form a square-wave cycle (Staddon, 1967). Experiment 1 demonstrated that abrupt transitions do not, by themselves, account for these failures. Our pigeons rapidly learned to track a single transition to shorter (step-down) or longer (step-up) interval durations, and appeared to do so based on the preceding IFI:

Decreases and increases in wait times were observed in the IFI immediately following a transition. However, the time course of wait times across subsequent poststep IFIs, and to a lesser extent across sessions, differed under the step-down and step-up conditions: Adaptation of wait times following a decrease in IFI duration was essentially complete within the first IFI and changed little across sessions, whereas wait times following an increase to longer IFIs adapted more slowly over several IFIs and often after more sessions.

These differences might explain why pigeons often fail to track sequences comprised of many nonprogressive transitions in IFI duration. Indeed, our pigeons were unable to maintain performance on a cyclic version of the IFIs used in the first experiment: By the end of training in Experiment 2, wait times were approximately the same duration in all IFIs. The failure to discriminate paralleled that found during steady-state performance on cyclic square-wave sequences (e.g., Innis & Staddon, 1970; Staddon, 1967) and triangular sequences that are similar to what we used (e.g., Innis, 1981). But, unlike previous experiments, we found strong evidence of tracking during the first session of exposure.

Our findings raise a number of issues. First, why were rapid timing effects not observed sooner? A primary difference between our study and earlier ones is that our IFIs were programmed according to an RID reinforcement schedule; earlier studies typically programmed each IFI according to a standard FI schedule. Thus, it is possible that our effects may depend on some aspect of RID schedules and not on the duration of IFIs per se. Perhaps the change in stimulus that accompanies the first response and/or not requiring a response at the end of the IFI engenders faster and better discrimination. However, it is unlikely that these factors played a role in our results. Shull (1970) measured postreinforcement wait times during FI and FT (fixed-time) reinforcement schedules that were accompanied by either no stimulus change or a stimulus change following the first response (his FT schedule with a stimulus change is equivalent to our RID schedule). He found that wait times were not affected by whether or not a response was required at the end of the programmed IFI or by whether or not the first peck produced a change in the stimulus. In all cases, the wait time appeared to depend on the duration of

the IFI. More recently, Wynne and Staddon (1992) found no significant difference in wait times on comparable RID and FI schedules with short (less than 23 s) IFIs. Instead, rapid timing probably remained unnoticed, until recently, because of the tacit assumption that discrimination is a slow process; thus, the data of interest were primarily those from steady-state performance (but see Ferster & Skinner, 1957, for data from initial sessions of exposure to FI schedules).

Another issue our experiments raise is, now that there is a method for studying the dynamics of time discrimination and some compelling data have been obtained, what do we know about the mechanism? Chiefly, we know that a simple version of linear waiting (e.g., Staddon et al., 1991; Wynne & Staddon, 1988) is only an approximation of a mechanism, working under a limited set of conditions. In particular, although behavior on cyclic sinusoidal sequences (e.g., Higa et al., 1991) appears to be well described by a linear waiting process, performance on simpler two-valued schedules, like the step-down and step-up sequences in Experiment 1 and the three-valued triangular sequence in Experiment 2, cannot be explained by the same process. Closer examination of the dynamic properties of timing suggest that prior IFIs, and not just the preceding one, affect behavior in complex yet orderly ways. The fact that wait times during a transition to longer IFIs adapt more gradually, within and across sessions, suggests that prior shorter IFIs have additive and persistent effects on behavior. These effects might explain why performance during a sequence with many transitions, from shorter to longer and longer to shorter IFIs, eventually deteriorates.

Several questions remain unanswered. For instance, we are unable to determine whether the number of prestep IFIs in Experiment 1 affected discrimination in different ways, because only a few sessions were used. It would also be interesting to know whether changes in the ratio of IFI durations would have generated different effects in our experiments. The complexity of possible interactions and effects suggests that concomitant to experimental analysis should be the testing of real-time models, like Staddon and Higa's diffusion-generalization model. Until further experiments are done and models developed, the effects of prior

IFIs—in an animal's recent and remote past—on temporal discrimination remain unclear.

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